Exploring the QCD Phase Diagram: RHIC Beam Energy Scan II

Daniel Cebra
University of California, Davis

For the STAR Collaboration

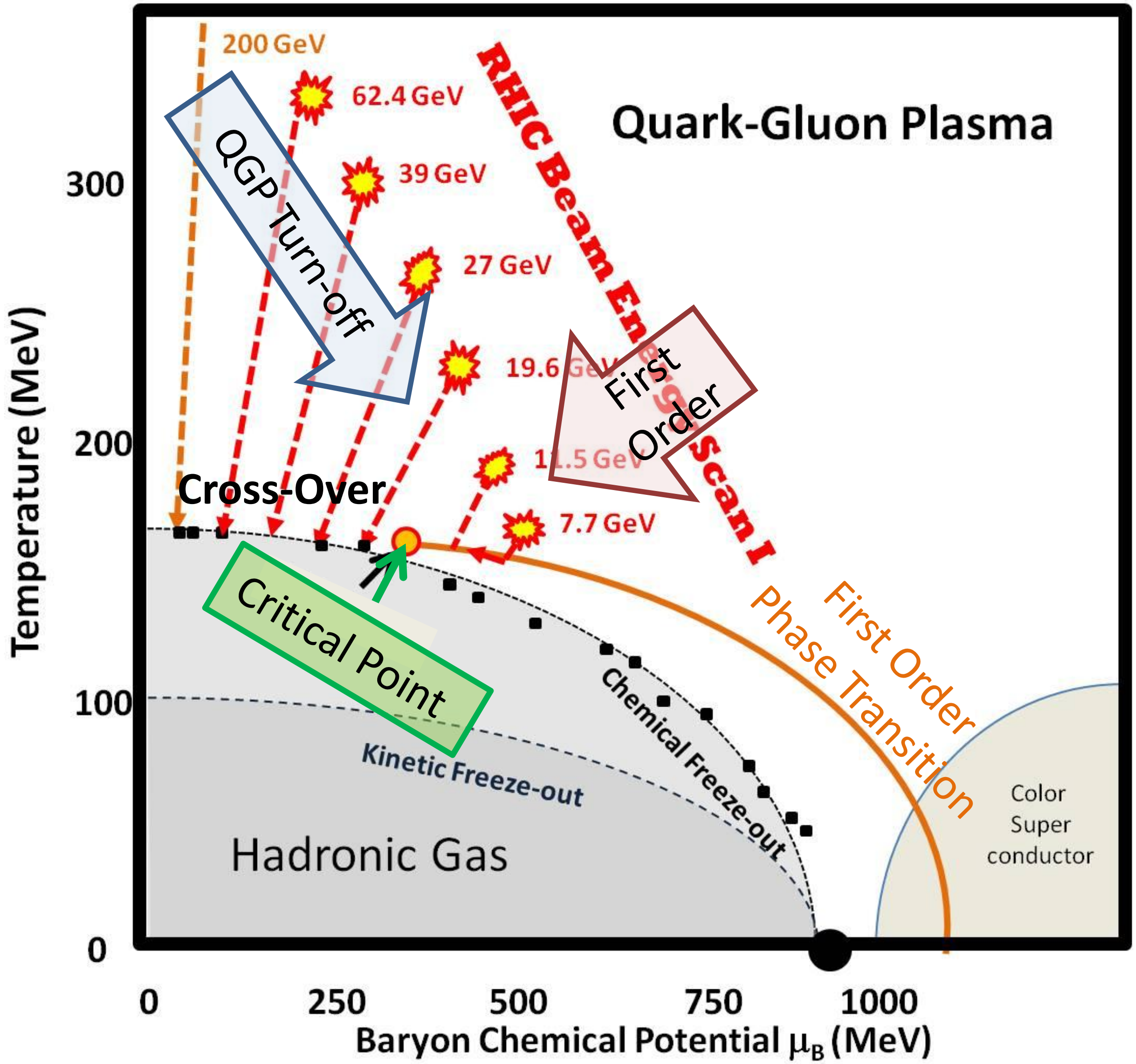
The RHIC Beam Energy Scan I

- We built RHIC to find the QGP.
  And we did it!

- But QGP is a new and complicated phase of matter. We have made huge progress in understanding its nature. At high energy, we expect a **cross-over** transition. At lower energy there should be a **first order** transition and a **critical point**.

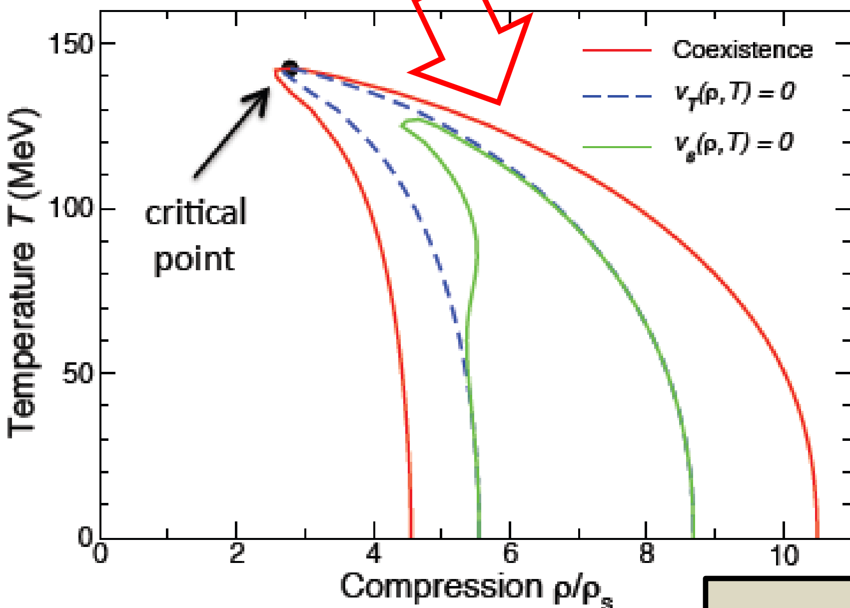
- The structure of the QCD matter phase diagram is **fundamental**. This will be in textbooks in future decades

- **Three Goals of BES program:**
  - **Turn-off of QGP signatures**
  - **Find critical point**
  - **First order phase transition**.



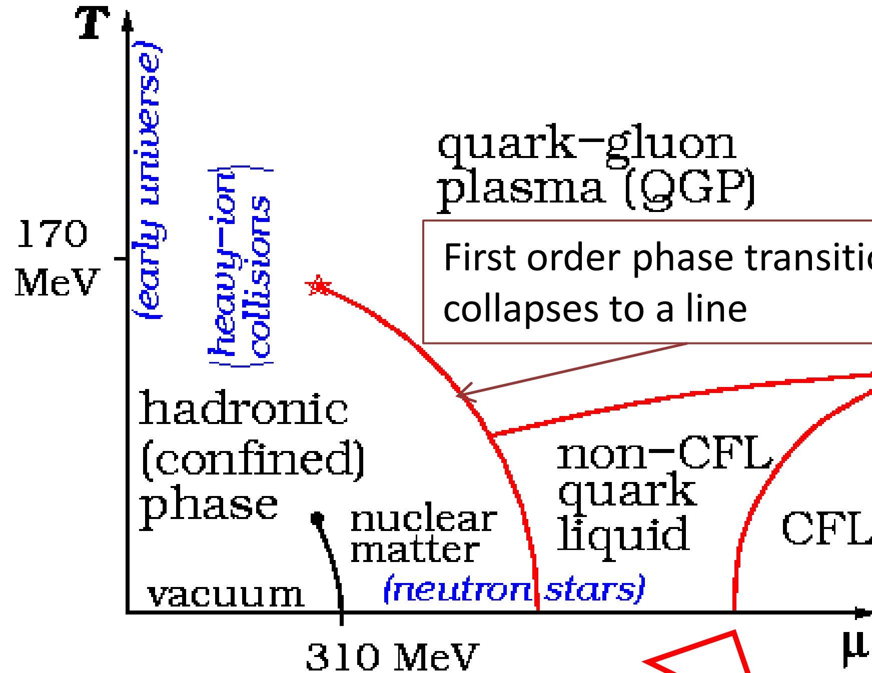
The QCD Matter Phase Diagram

A phase diagram might more intuitively be shown in Temperature versus density space



$v_T = 0$: isothermal spinodal

$v_s = 0$: isentropic spinodal

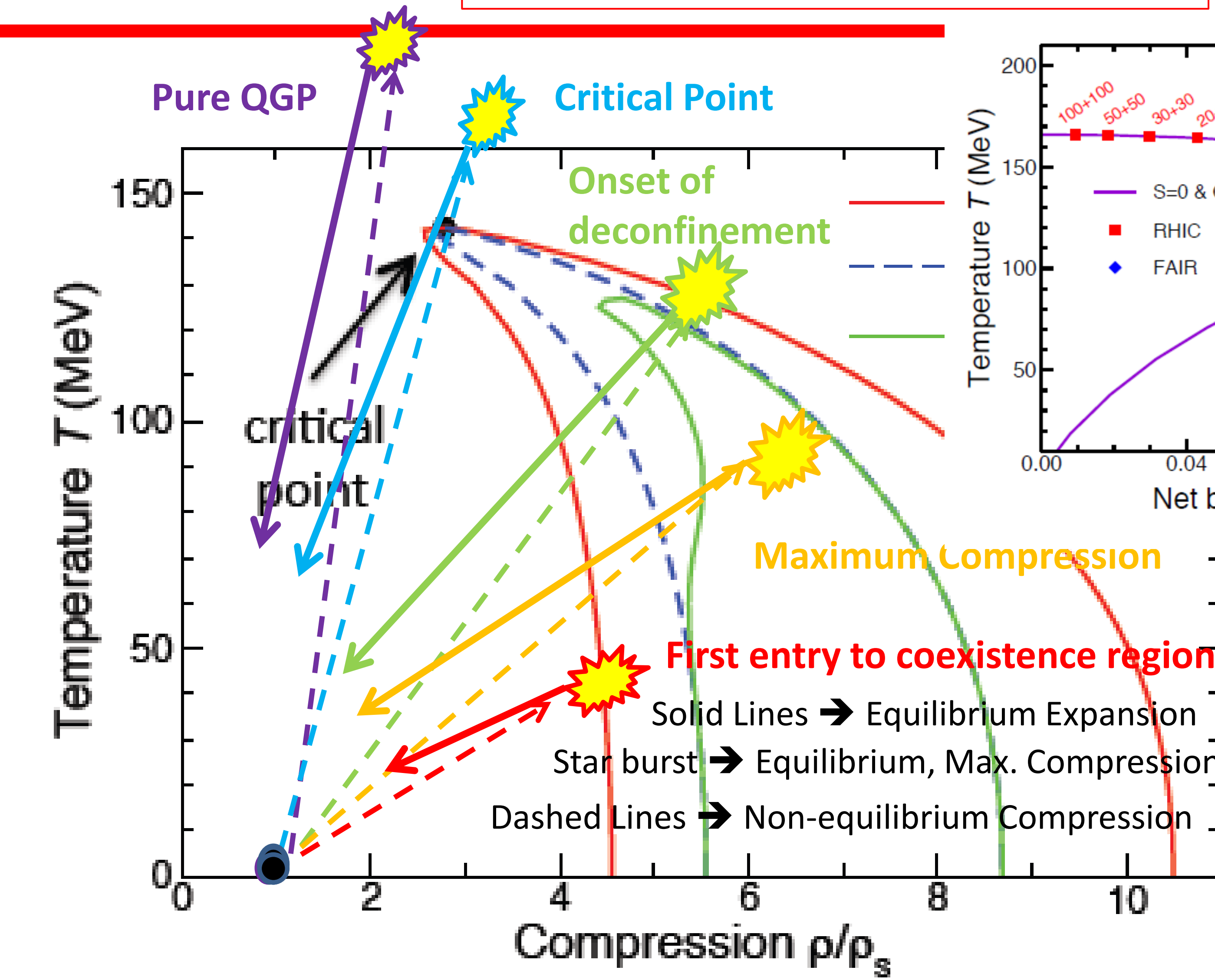


First order phase transition collapses to a line

$$\frac{d^6N}{dx^3dp^3} = g \ln\left(\frac{1}{e^{\frac{E-\mu}{T}} \pm 1}\right)$$

We can not measure compression, volume, or density, so we instead use chemical potential, μ

Reaction Trajectories



Note:
- NA49 suggests that the onset of deconfinement is achieved at 7.7 GeV
- Randrup predicts maximum compression at 7.7 GeV

Overview of the Beam Energy Scan I Results

STAR

1. **Turn-off of QGP signatures:**
   - **NCQ breaks down below 19.6 GeV**
   - **High p_t suppression not seen below 19.6 GeV**
   - **LPV effect not seen below 11.5 GeV**

Clear Evidence

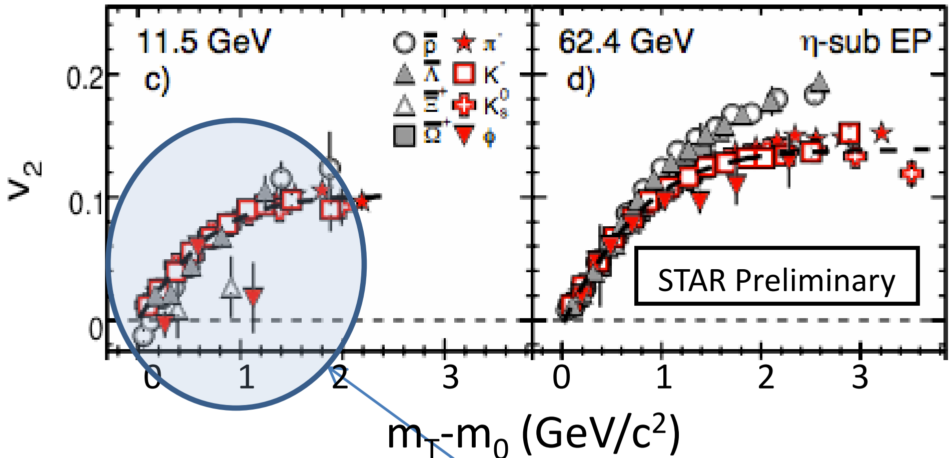
2. **Evidence of the first order phase transition.**
   - **v_1 sign change above 7.7**
   - **Inflection in v_2 and $dE_T/d\eta$ at 7.7**
   - Azimuthal HBT signal inconclusive

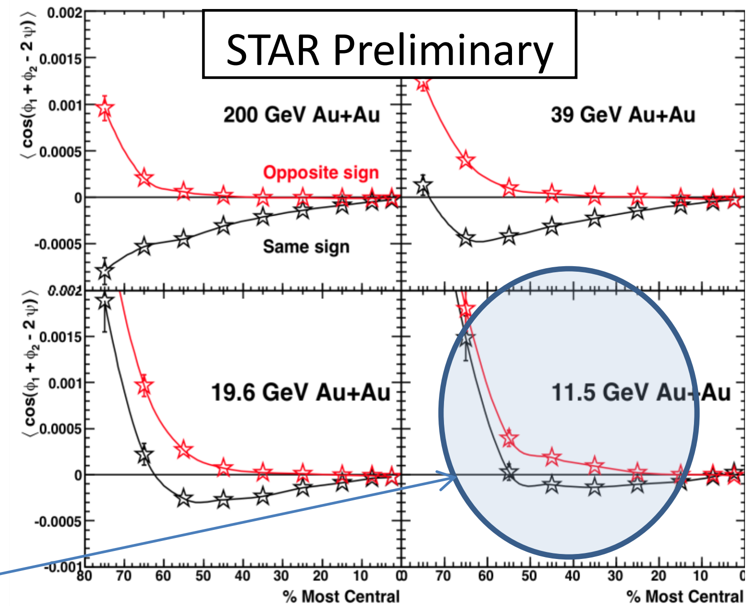
Hints

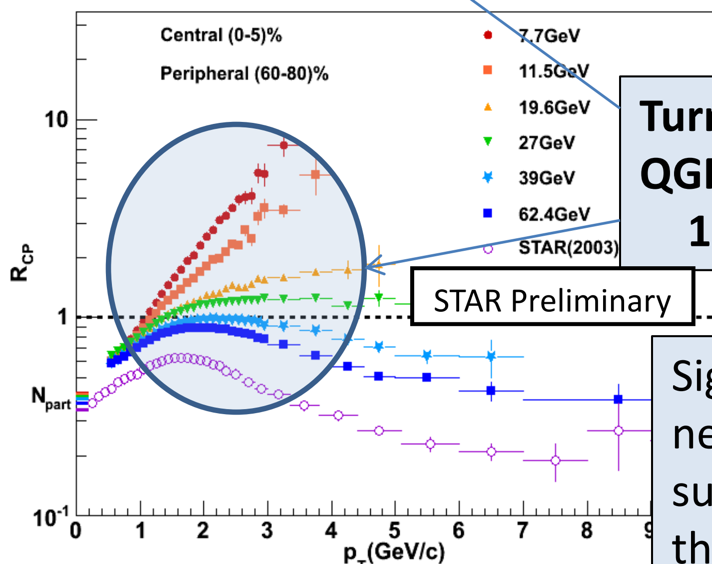
3. **Search for the critical point.**
   - K/π, K/p, or p/π fluctuations are not conclusive.
   - Higher moments of the proton distributions

More Data

Turn-off of QGP Signatures

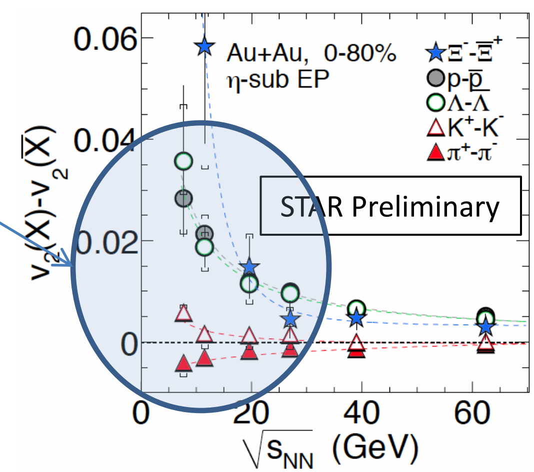






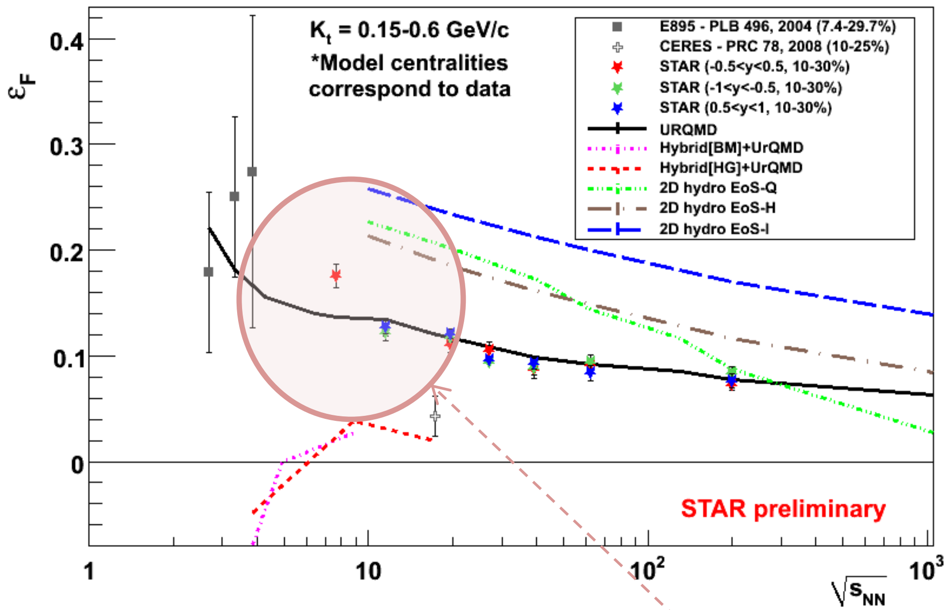
Turn-off of key QGP signatures 19.6 – 11.5

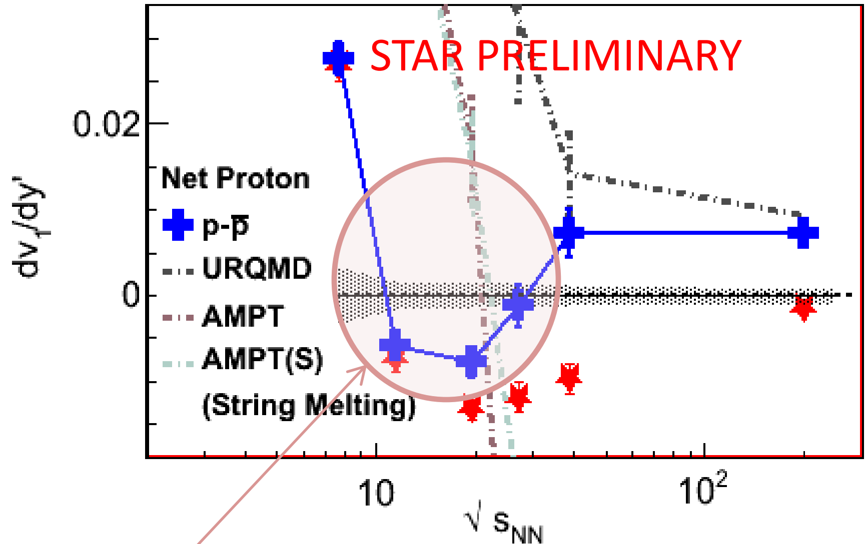
Signature turn-off is necessary but not sufficient to demonstrate the QGP is not reached

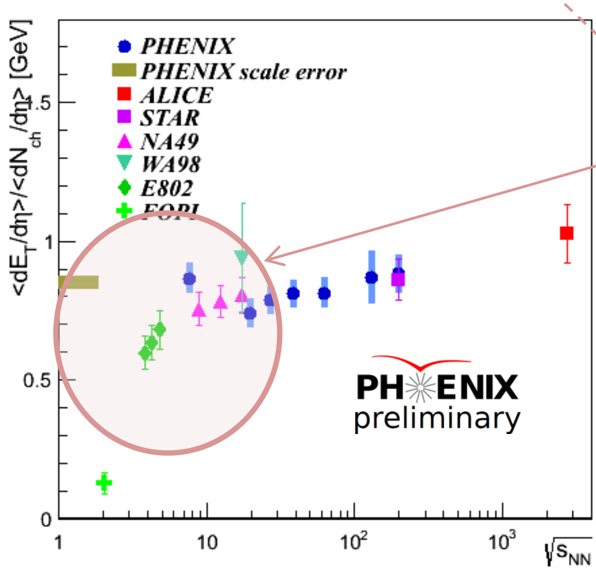


Search for 1st Order PhaseTransition

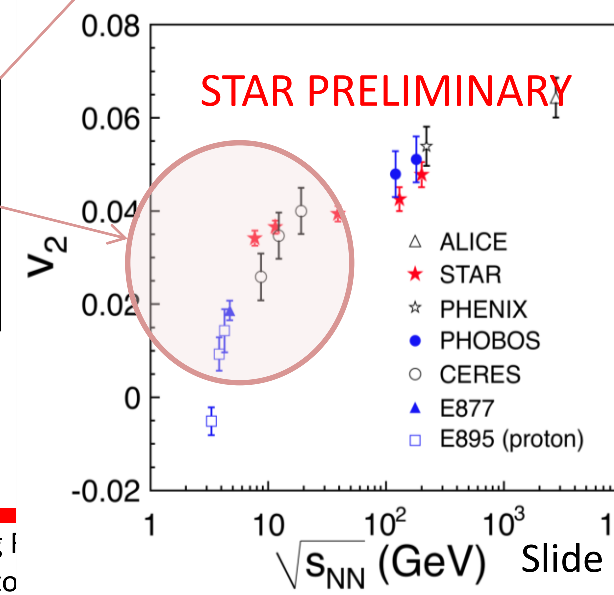
Excitation function for freeze-out eccentricity, ε_F







Hints of change in behavior at the low end of the energy range

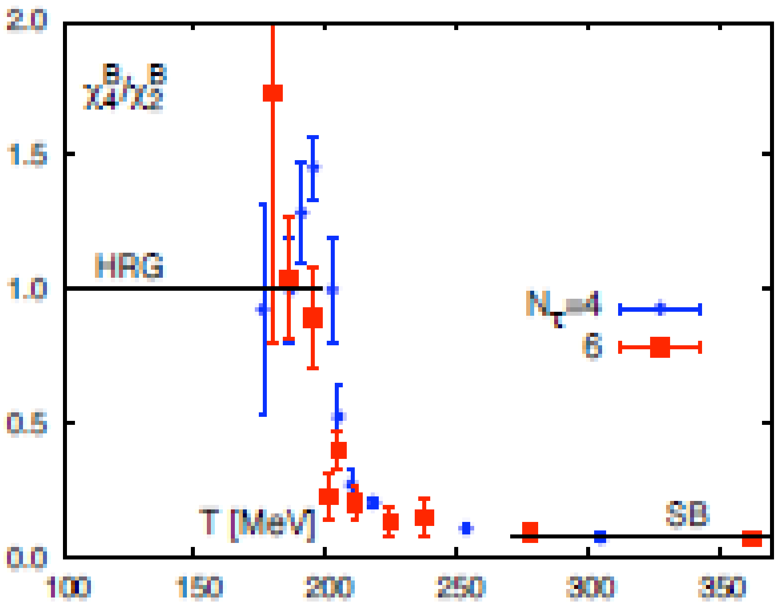


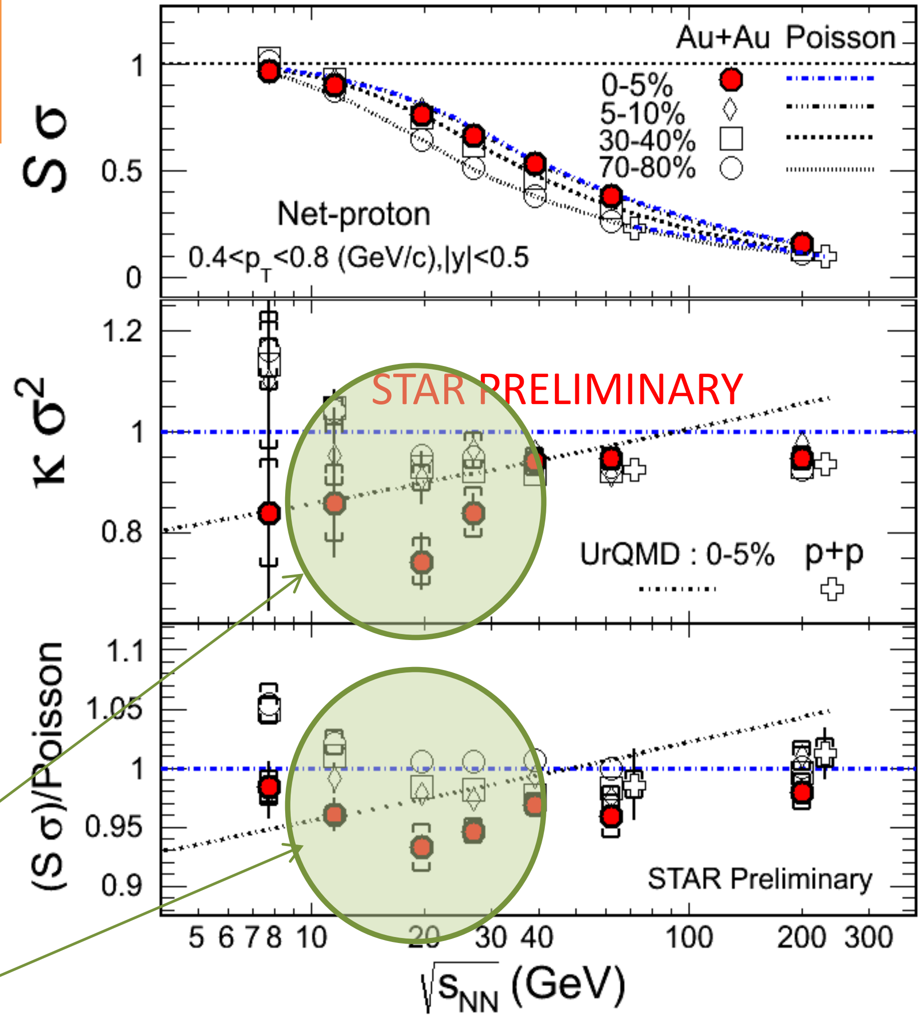
Search for the Critical Point

Volumes cancel

$$\chi_B^{(n)} = \left.\frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}\right|_T$$

$$\chi_B^{\ 4} / \chi_B^{\ 2} = (\kappa\sigma^2)_B$$
$$\chi_B^{\ 3} / \chi_B^{\ 2} = (S\sigma)_B$$





Deviations from Poisson in the lower half of the BES energy range

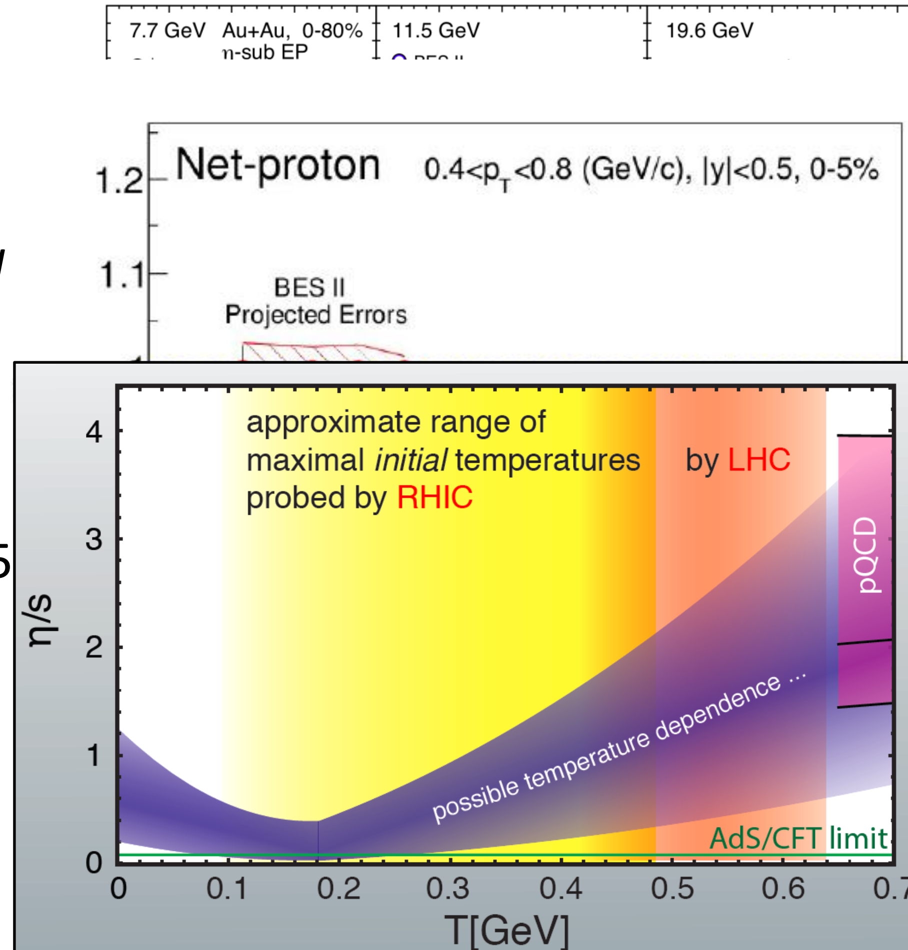
Need more statistics or finer energy steps

What Have We Learned? What Needs to be Done?

1) The key QGP *signatures* disappear below 19.6

2) First order phase transition or Onset of deconfinement *likely* at the lower end of the range
   - *low energy performance is critical*

3) Critical Point will need more statistics
   - Do we need finer steps? Over 100 MeV Gap in μ_B between 11.5 and 19.6



4) Determination of the temperature dependence of transport properties

Beam Energy Scan II: Answering the remaining questions

$\sqrt{S_{NN}}$ (GeV)	19.6	14.6	11.5	7.7
μ_B (GeV)	205	250	315	420
BES I (MEvts)	36	---	11.7	4.3
BES II (MEvts)	**400**	**100**	**120**	**80**

- Finer steps in μ_B
- High Statistics

Critical Point

Onset of Deconfinement

But that's a lot of data… at current rates, this would take ~70 weeks of RHIC operations! Isn't there a better way? ➔ Yes! We can cool the beams!

Outlook – BES-II

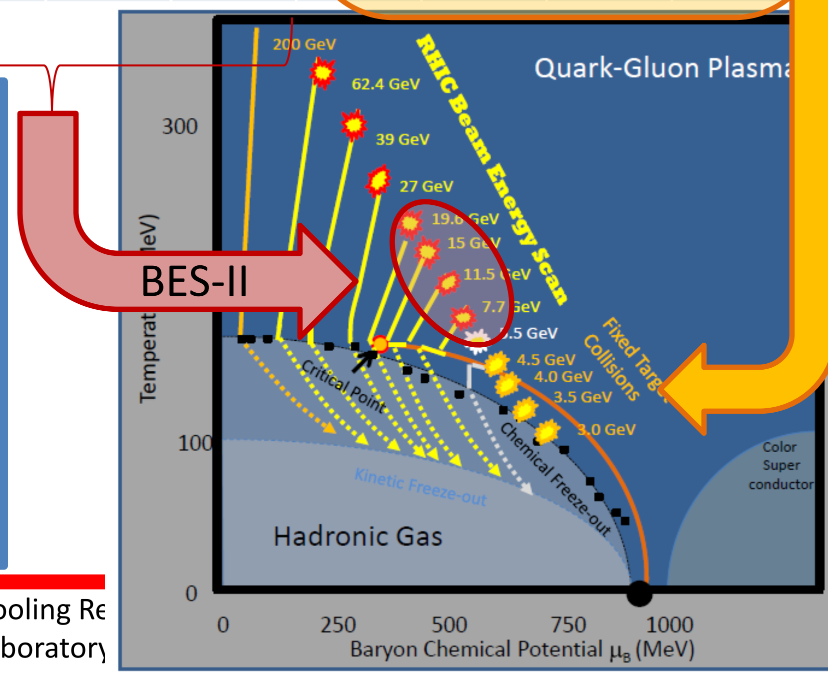
$\sqrt{S_{NN}}$ (GeV)	62.4	39	27	19.6	14.6	11.5	7.7	4.5	3.9	3.5	3.0
μ_B (MeV)*	70	115	155	205	250	315	420	585	630	670	720
BES I (MEvts)	67	130	70	36	---	11.7	4.3				
Rate(MEvts/day)	20	20	9	3.6	1.6	1.1	0.5				
BES II (MEvts)	---	---	---	400	100	120	80	5	5	5	5
eCooling	---	---	---	8	6	4.5	3				
Beam (weeks)	---	---	---	2	1.5	3.5	7.5				

Fixed Target Collisions

* J. Cleymans, H. Oeschler, K. Redlich, S. Wheaton, PR C73, 034905 (2006).

SRF Gun

- We have now put forward a BES-II proposal to focus on the most interesting region
- Electron cooling is key to the feasibility of this proposal
- eCooling will take a few years
- Expect BES-II in 2017-2019



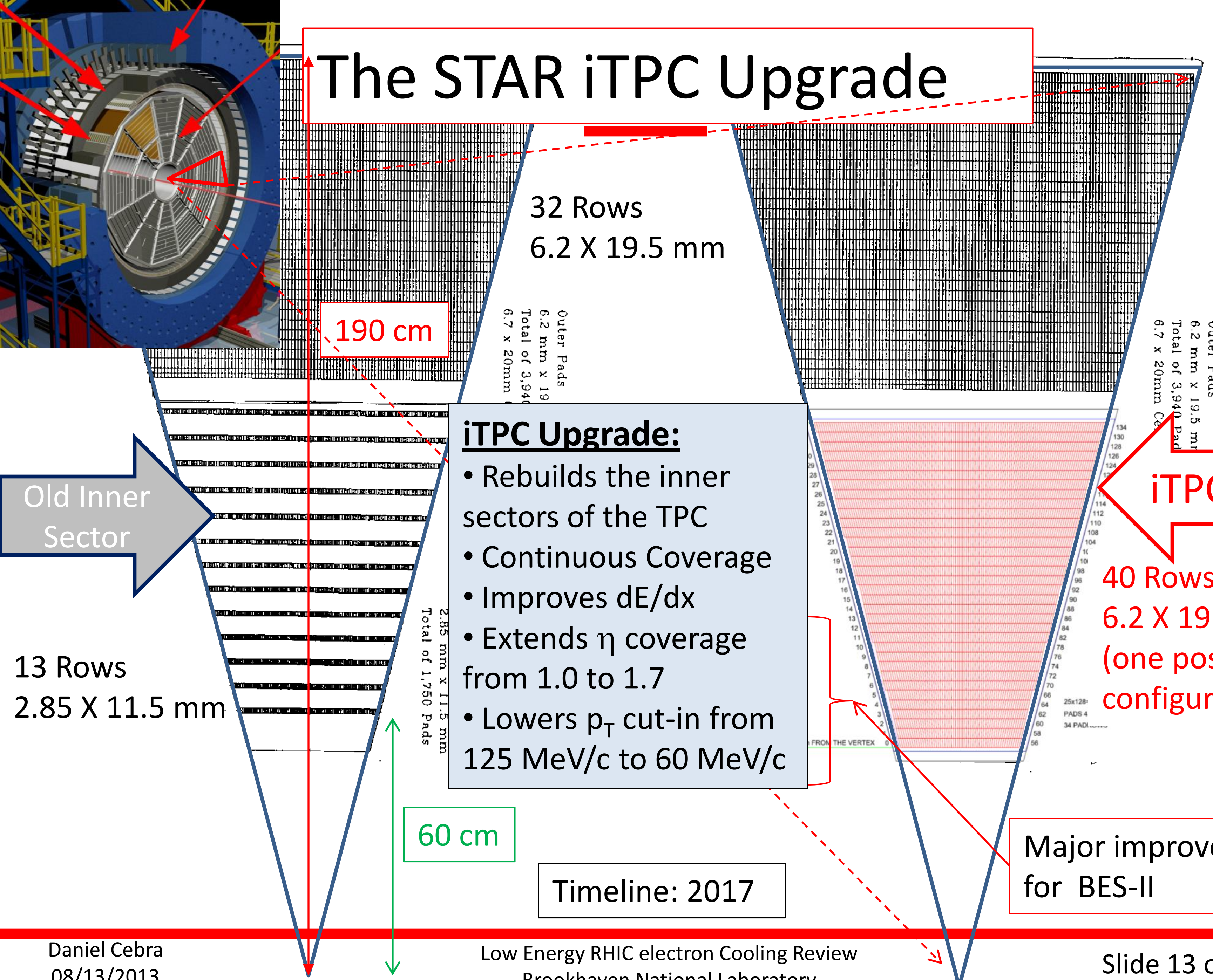
TimeLine Drivers

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2013	• 500 GeV $\vec{p}+\vec{p}$ • 15 GeV Au+Au	• Sea antiquark and gluon polarization • QCD critical point search	• Electron lenses • upgraded pol'd source • STAR HFT
2014	• 200 GeV Au+Au and baseline data via 200 [illegible]eeded for [illegible]bsystems)	• Heavy flavor flow, energy loss, thermalization, etc. • quarkonium studies	• 56 MHz SRF • full HFT • STAR Muon Telescope Detector • PHENIX Muon Piston Calorimeter Extension (MPC-EX)
2015-2017	• High stat. Au+Au at 200 and ~40 GeV • U+U/Cu+Au at 1-2 energies • 200 GeV p+A • 500 GeV $\vec{p}+\vec{p}$	• Extract $\eta/s(T_{min})$ + constrain initial quantum fluctuations • further heavy flavor studies • sphaleron tests @ $\mu_B \neq 0$ • gluon densities & saturation • finish p+p W prod'n	• Coherent Electron Cooling (CeC) test • Low-energy electron cooling • STAR inner TPC pad row upgrade
2018-2021	• 5-20 GeV Au+Au (E scan phase 2) • long 200 GeV + 1-2 lower $\sqrt{s}$ Au+Au w/ upgraded dets. • baseline data @ 200 GeV and lower $\sqrt{s}$ • 500 GeV $\vec{p}+\vec{p}$ • 200 GeV $\vec{p}+A$	• x10 sens. increase to QCD critical point and deconfinement onset • jet, di-jet, γ-jet quenching probes of E-loss mechanism • color screening for different qq states • transverse spin asyms. Drell-Yan & gluon saturation	• sPHENIX • forward physics upgrades

Note: This will be a 3 week run in 2014, without cooling, ➔lower statistics (30-40M) Still need to come back to this energy later

The BES II program needs electron cooling and it Needs the iTPC upgrade

The STAR iTPC Upgrade



iTPC Upgrade:

- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.7
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

Timeline: 2017

Major improvements for BES-II

BES Phase II – Relationship to TPC Upgrade

The TPC inner sector upgrade is critical for three reasons:

1) It reduces the low p_t cut-in threshold
2) It extends the accessible rapidity range

Important for fluctuation studies

Important for directed flow

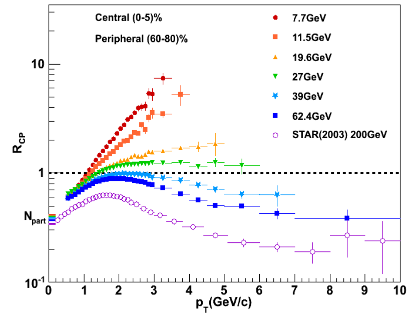
3) Improves dE/dx resolution

The TPC inner sector upgrade is especially important for the fixed target program:

4) For fixed target events, mid-rapidity will between 1.0 and 1.5, depending on collision energy. The iTPC will extend the TPC coverage forward of mid-rapidity.

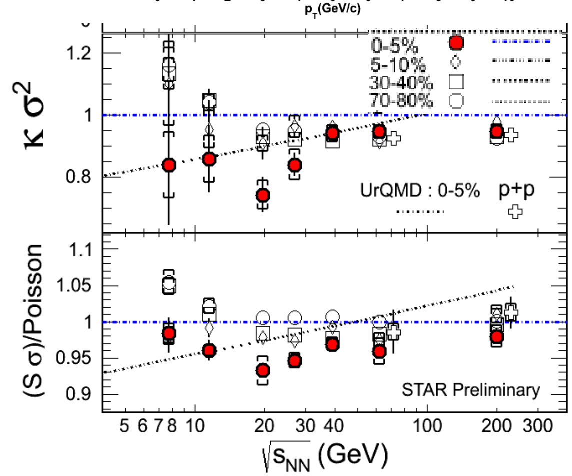
High Energy Range Drivers

- Above what energy does the system seem to behave like a QGP?



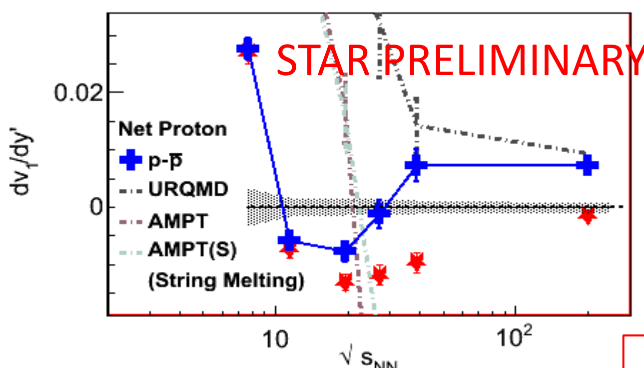
➔ Consistently we see QGP signatures at 19.6 and above. But even at this energy, the trajectory might pass through a critical point.

- Where do we see evidence for the critical point?



➔ The fluctuations at 19.6 seem to exhibit the largest deviation, however the fluctuations at 27 GeV also seem to deviate from baselines.

- Where do we no longer see evidence of a softening of the EOS?

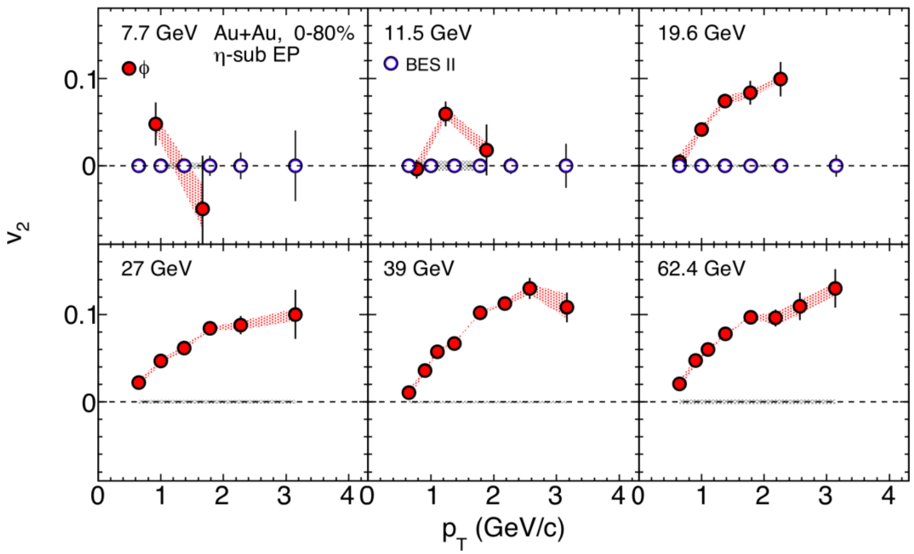


➔ The proton directed flow would suggest that reaction trajectories cross the coexistence region for beam energies from 7.7 to 27.

➔ Ideal reach would be to 27 GeV

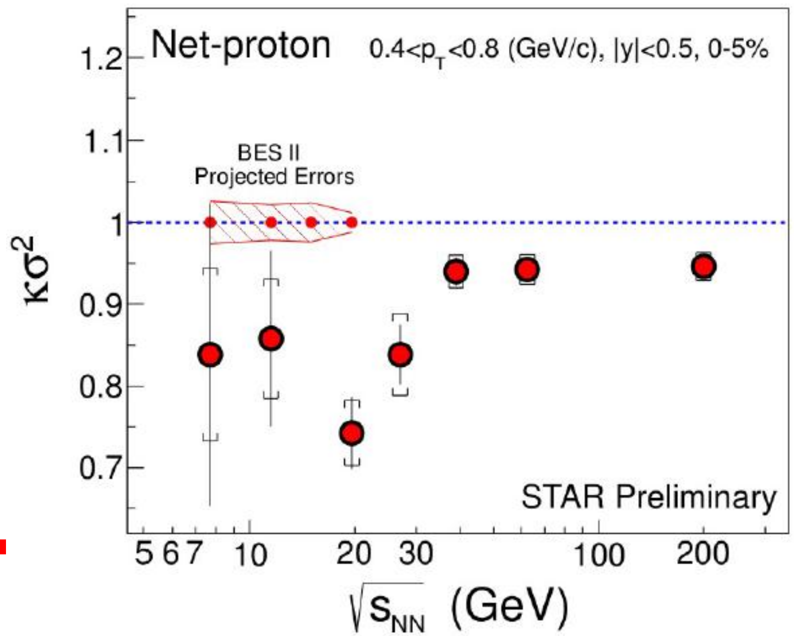
Statistics Drivers

Flow of the phi meson:
The ϕ is a meson with the mass of a baryon and with only created quarks (s – s_{bar}).
This is key for understanding dependence of flow on the quark content.



The most critical are the high p_t data points. We need to be able to make this measurement out to 3 GeV/c. This plot shows the error projections for 80, 120, 400 Mevts.

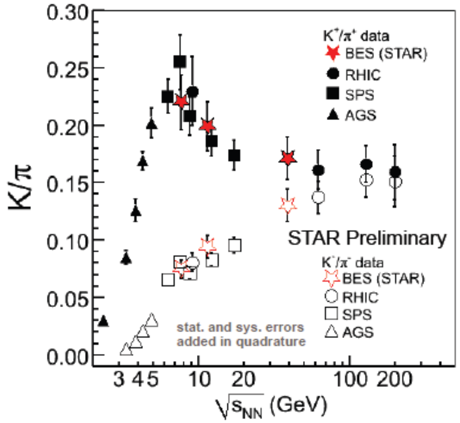
Higher Moments/ Fluctuations:
The higher moments of conserved quantities are sensitive to critical behavior, however finite size effects wash out the signal. Significantly better resolution is needed.



The errors on the net-proton kurtosis get larger where the signal starts to show deviations. We need the errors in the 7.7 to 19.6 range to be comparable to the higher energies.

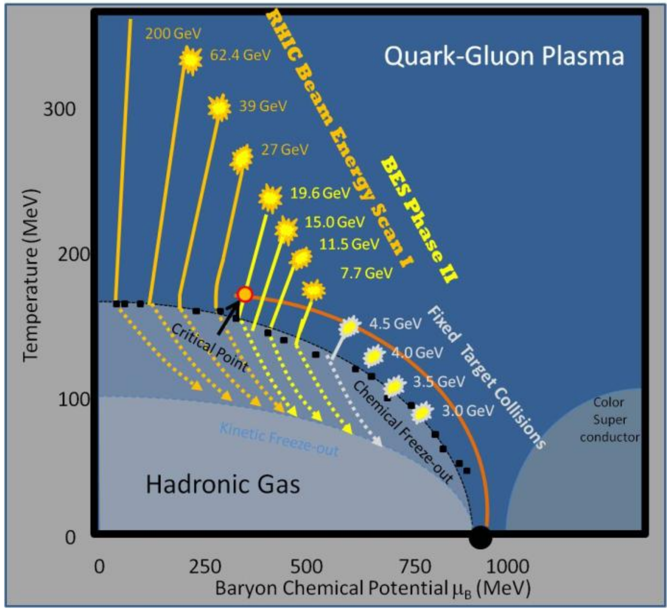
Low Energy Range Drivers

- NA49 suggests the onset of deconfinement at 7.7 GeV.



- STAR/AGS data suggest an inflection in the magnitude of the elliptic flow around 7.7 GeV.

- STAR data show the directed flow going negative above 7.7 GeV



- PHENIX/AGS data suggest an inflection in the generation of transverse energy around 7.7 GeV

- → We will need to take data below 7.7 GeV to verify that this is real change in behavior and not an artifact.

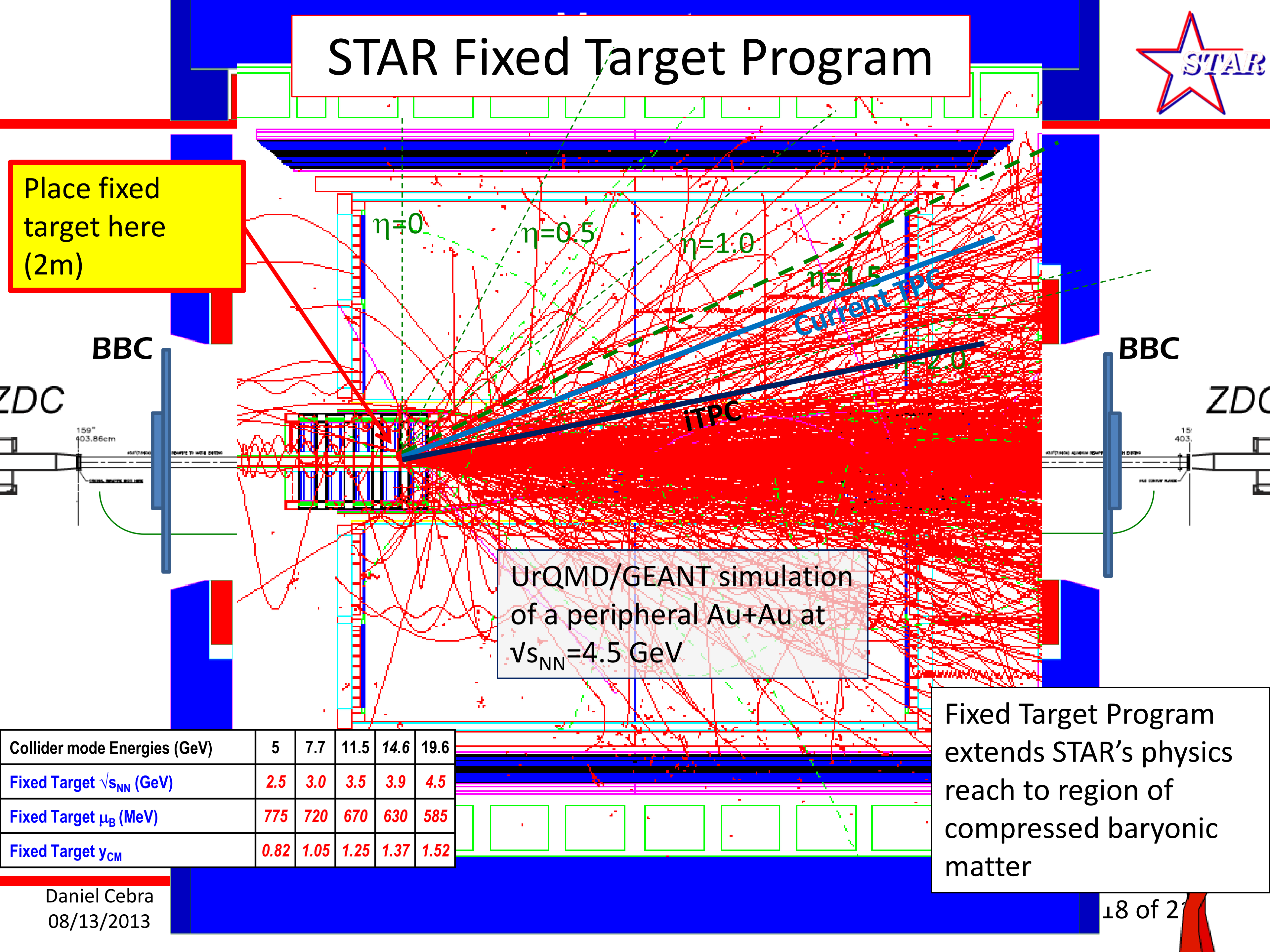
- STAR can achieve lower energies by using a fixed-target (range from 2.5 to 4.5 GeV), but we need to calibrate/verify by running the same energy in collider mode. (Two overlap options: 7.7 GeV or 5 GeV)

Collider Mode	Fixed-Target Mode
62.4 GeV	7.7 GeV
19.6 GeV	4.5 GeV

→ Ideal if collider could go as low as 5.0 GeV

STAR Fixed Target Program

Place fixed target here (2m)



UrQMD/GEANT simulation of a peripheral Au+Au at $\sqrt{s_{NN}}$=4.5 GeV

Fixed Target Program extends STAR's physics reach to region of compressed baryonic matter

Collider mode Energies (GeV)	5	7.7	11.5	14.6	19.6
Fixed Target $\sqrt{s_{NN}}$ (GeV)	2.5	3.0	3.5	3.9	4.5
Fixed Target μ_B (MeV)	775	720	670	630	585
Fixed Target y_{CM}	0.82	1.05	1.25	1.37	1.52

Step Size Drivers

- We have been criticized by theorists for having too large a step size in μ_B.
- The argument is that we could miss the critical point. And that we should not have a step size larger than 50 MeV.
- There is a balance between step size and statisitcs.
- There are clearly still some gaps to be filled.
- The ability to survey energies will be important.

A few possible energies

$\sqrt{s_{NN}}$ (GeV)	62.4	39	27	19.6	14.6	11.5	9.1	7.7	6.4	5.0	4.5	3.9	3.5	3.0
μ_B (MeV)*	70	115	155	205	250	315	370	420	480	555	585	630	670	720
BES I (MEvts)	67	130	70	36	---	11.7		4.3						
Rate(MEvts/day)	20	20	9	3.6	1.6	1.1		0.5						
BES II (MEvts)	---	---	---	400	100	120		80			5	5	5	5
eCooling	---	---	---	8	6	4.5		3						
Beam (weeks)	---	---	---	2	1.5	3.5		7.5						

Fixed Target Collisions

Ideal BES phase II

- High luminosity
- Fine energy step size
- Low energy range down to 5.0 GeV
- High energy range up to 27 GeV

However, realistically we can not have everything.
Therefore we must prioritize.

Conclusions – BES Phase II

Although several questions have been answered by data from BES-I, there are still some important open questions that we need more data to answer conclusively.

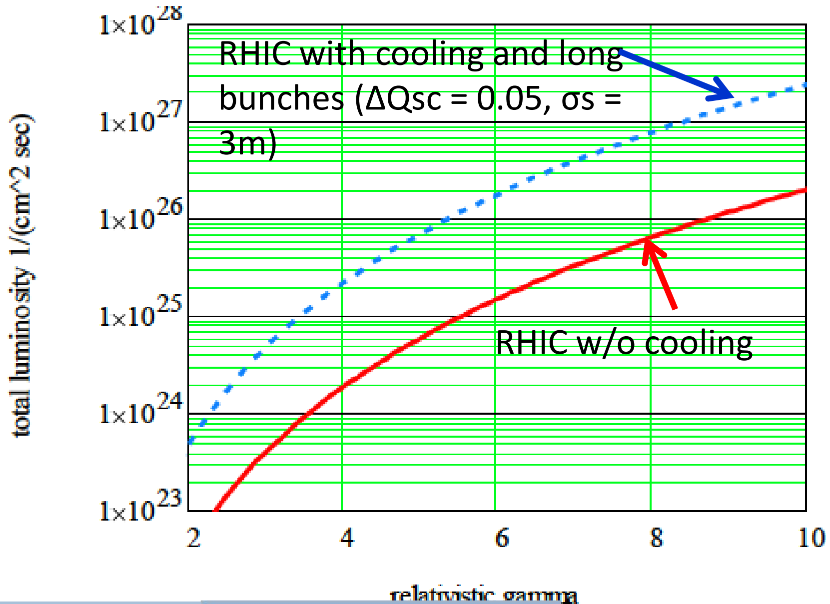
- Therefore we have proposed BES-II with 10-20 times better statistics.
- This will need electron cooling, which is being developed by CAD.
- The iTPC upgrades will provide extended η coverage and lower p_T cut-ins.
- The Fixed target program will extend BES-II physics reach to the region below the onset of deconfinement.
- All these developments will be ready for a second low energy run at RHIC in the time frame from 2017-2020.

Backup

Low Energy Electron Cooling at RHIC

Electron Cooling can raise the luminosity by a factor of 3-10 in the range from 3 – 10 GeV

Long Bunches increase luminosity by factor of 2-5

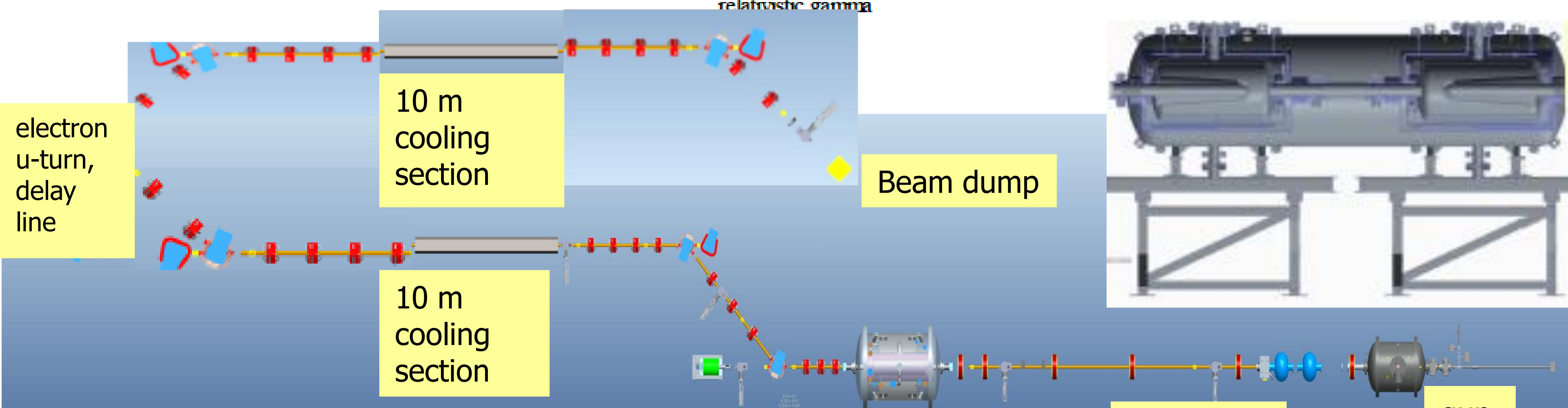


Implimentation in phases:

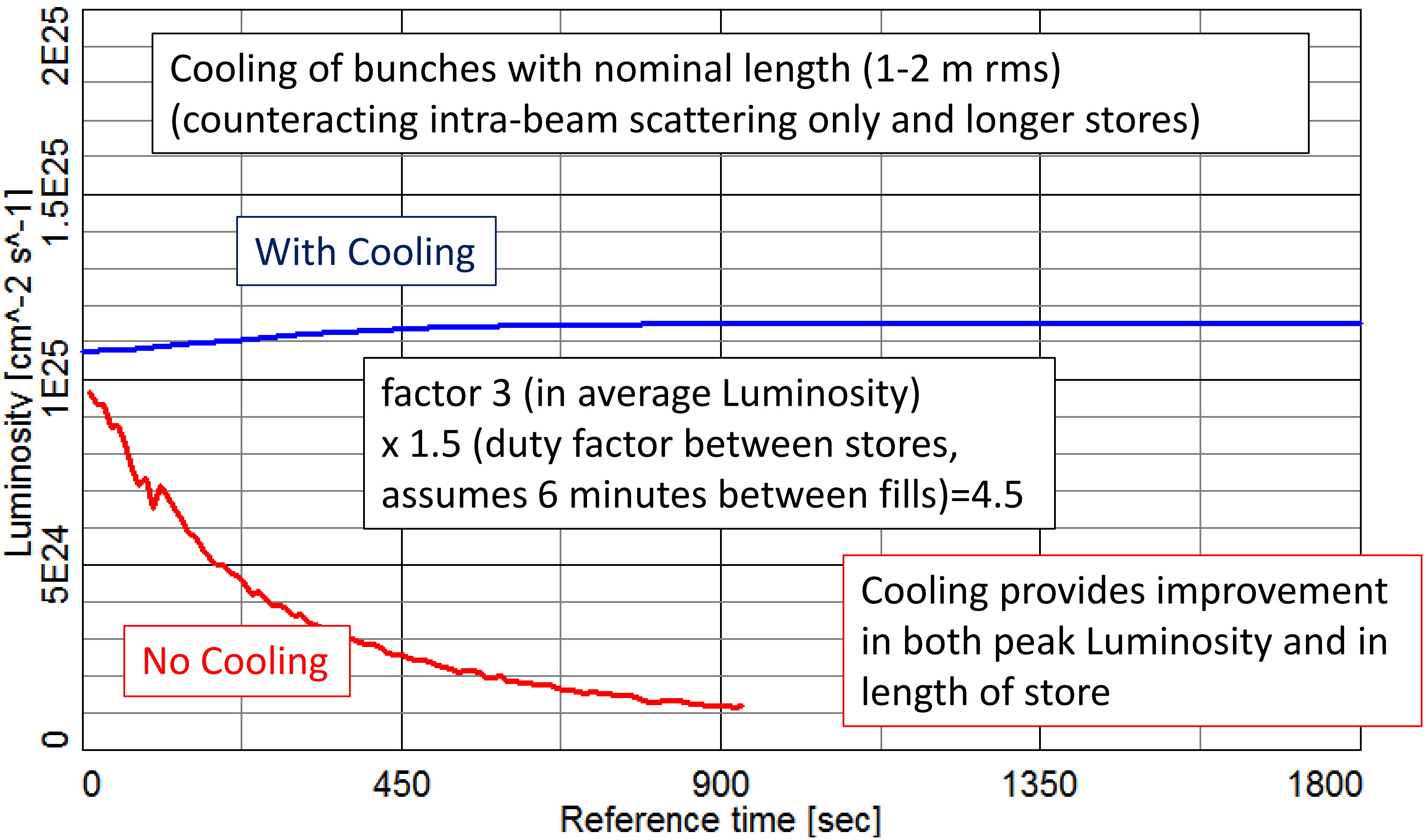
Phase I (2017)
$\sqrt{s_{NN}}$ = 5-9 GeV

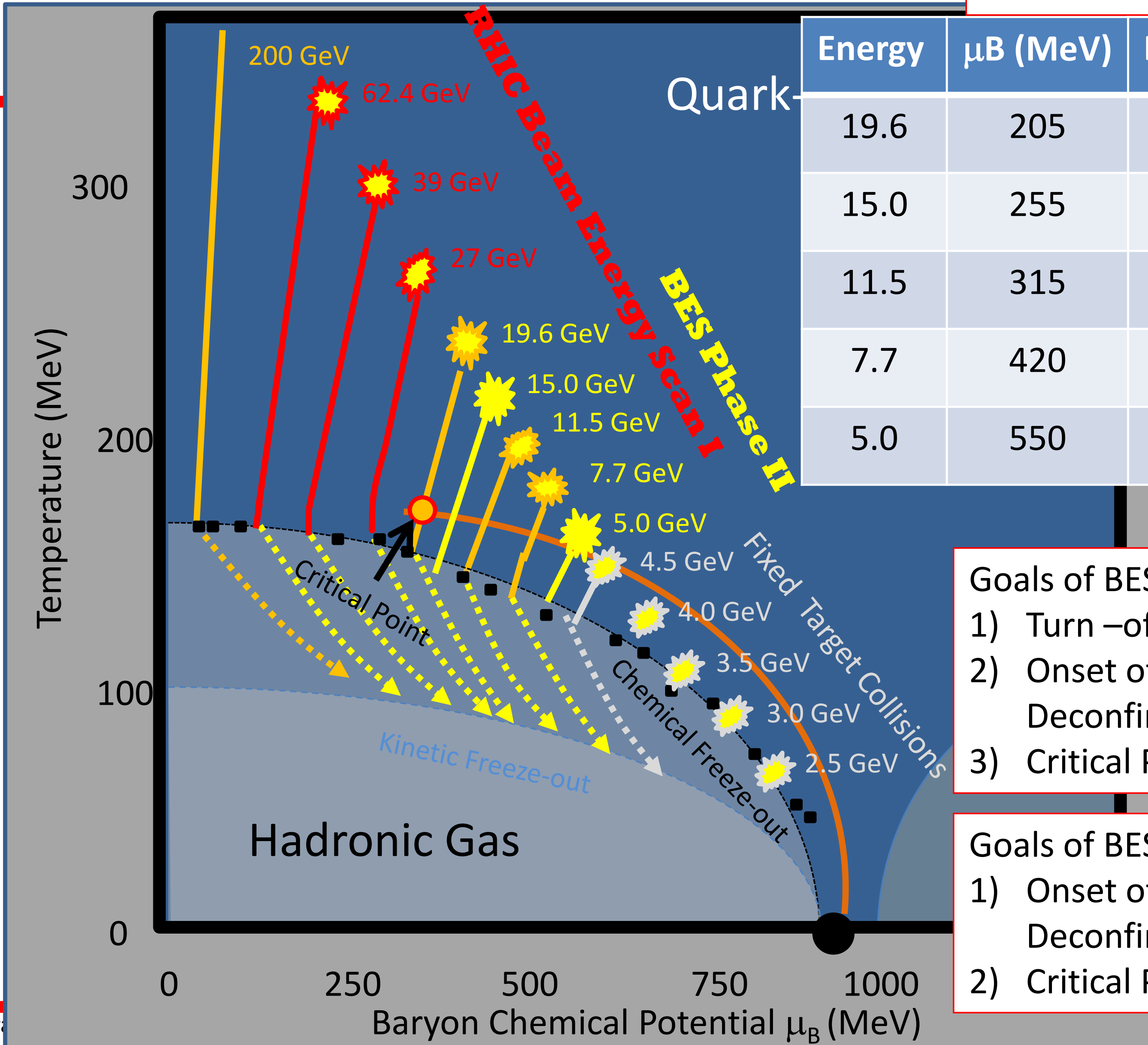
Phase II (2018+)
[additional 3 MeV booster cavity]
$\sqrt{s_{NN}}$ = 9-20 GeV

SRF Gun



Simulation of luminosity with electron cooling at beam energy of 3.85 GeV/n ($\sqrt{s_{NN}}$ =7.7 GeV).





BES Phase II

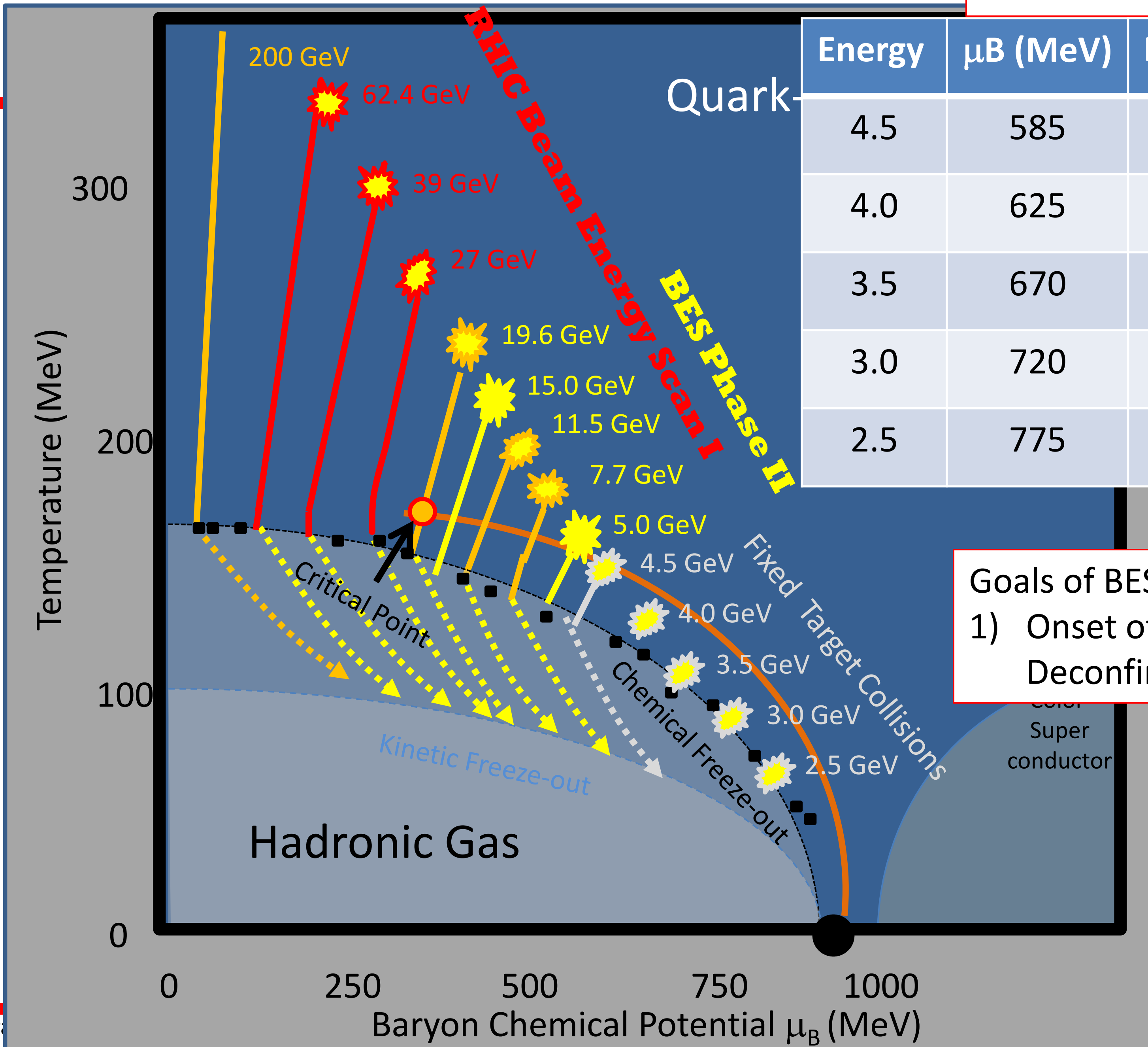
Energy	μB (MeV)	Events (M)
19.6	205	150
15.0	255	150
11.5	315	50
7.7	420	70
5.0	550	TBD

Goals of BES I:
1) Turn –off of QGP
2) Onset of Deconfinement
3) Critical Point

Goals of BES II:
1) Onset of Deconfinement
2) Critical Point

BES Phase II+

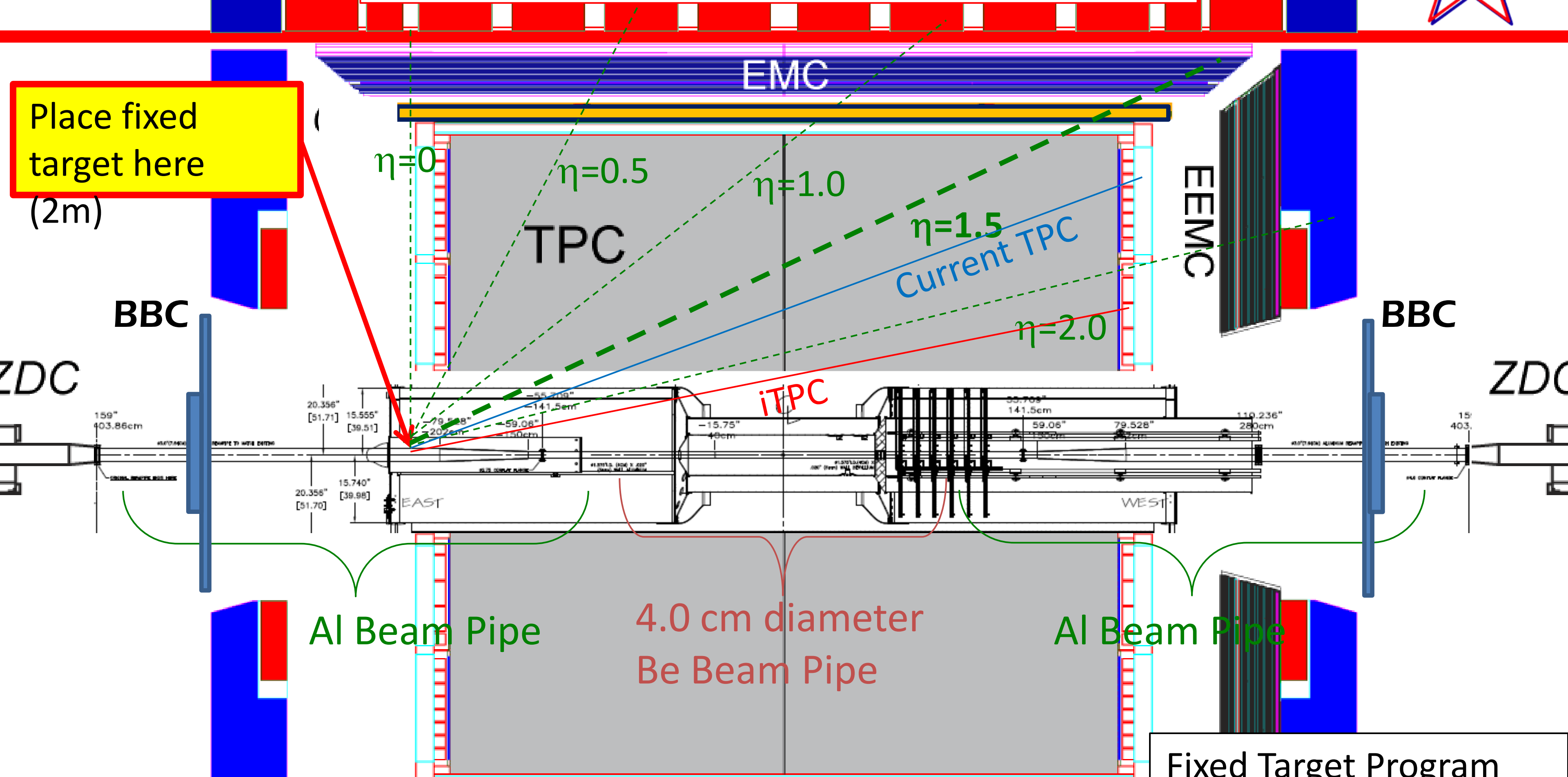
Energy	μB (MeV)	Events (M)
4.5	585	10
4.0	625	11
3.5	670	13
3.0	720	15
2.5	775	20



Goals of BES II+:

1) Onset of Deconfinement

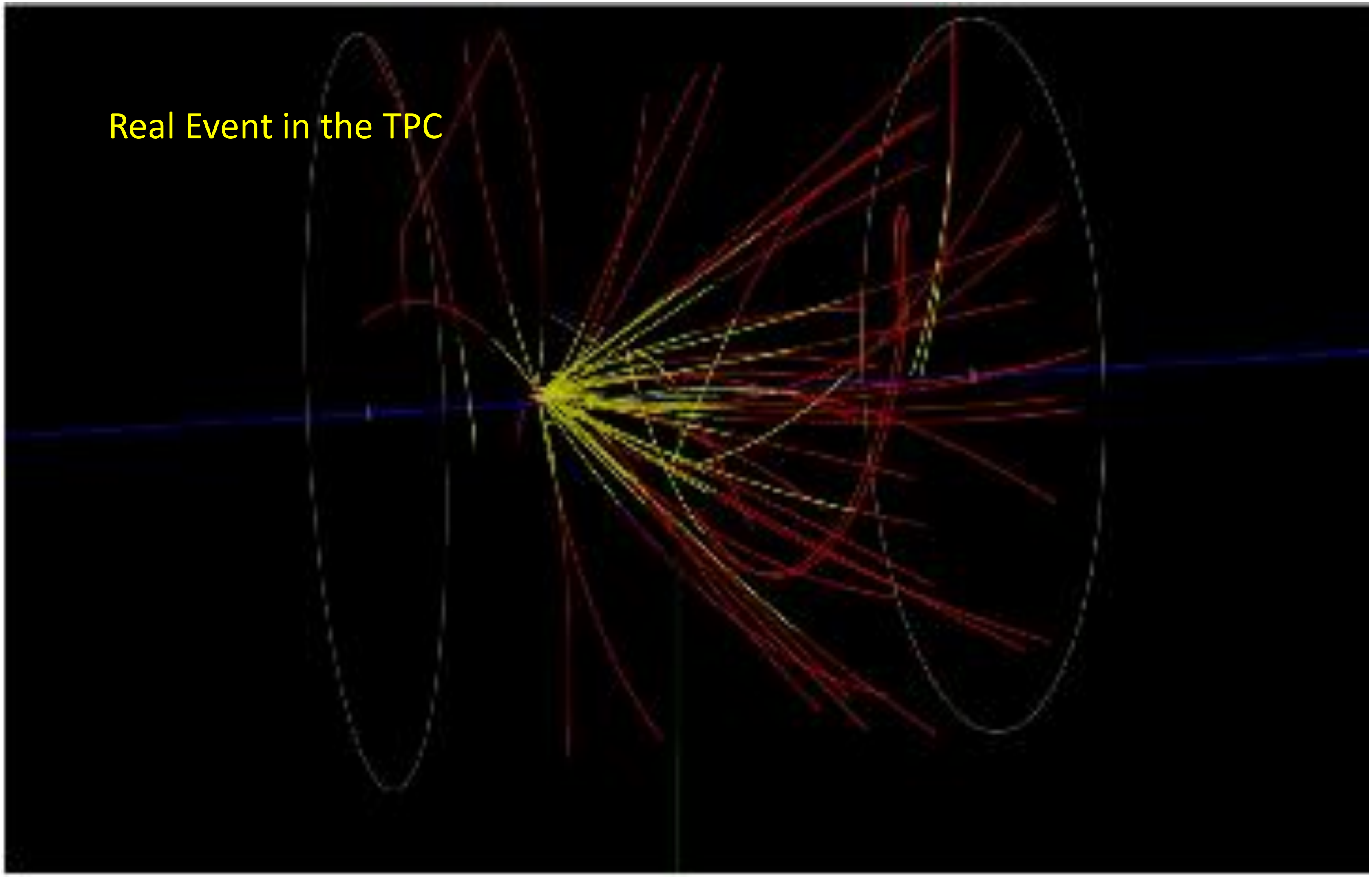
STAR Fixed Target Program



Collider mode Energies (GeV)	5	7.7	11.5	15	19.6
Fixed Target $\sqrt{s_{NN}}$ (GeV)	2.5	3.0	3.5	4.0	4.5
Fixed Target μ_B (MeV)	775	720	670	625	585
Fixed Target y_{CM}	0.82	1.05	1.25	1.39	1.52

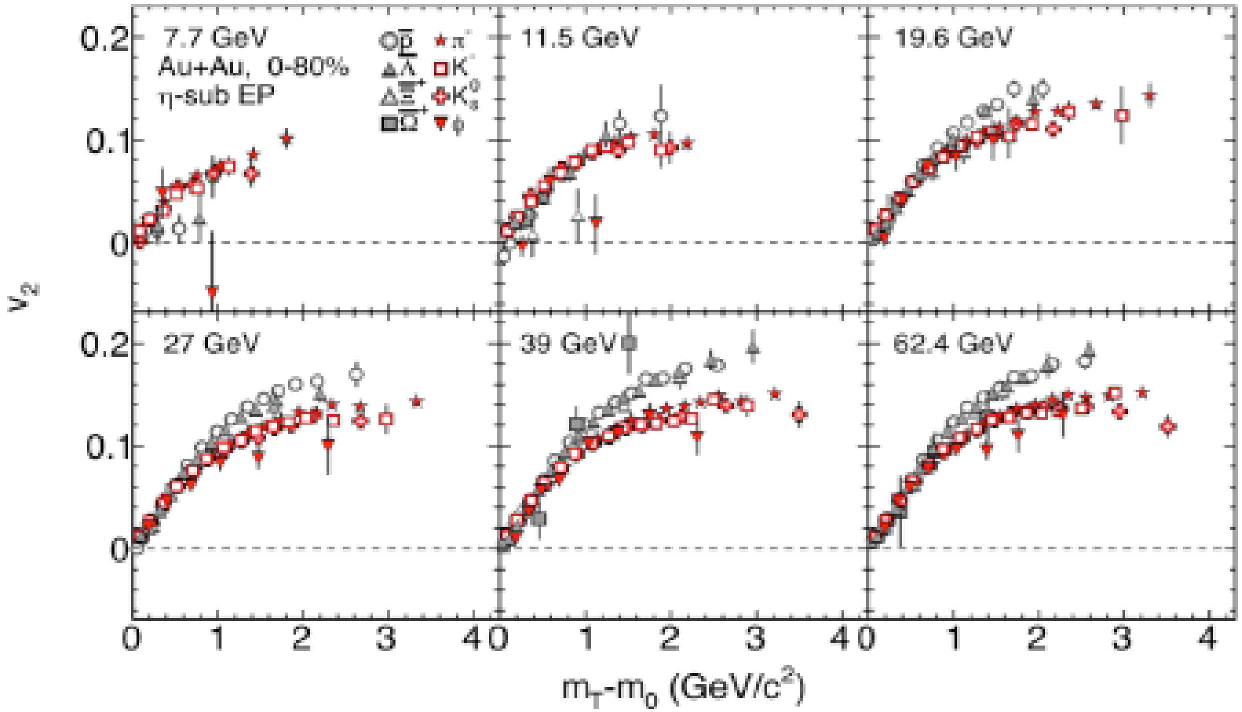
Fixed Target Program extends STAR's physics reach to region of compressed baryonic matter

BES Phase II+ Fixed Target



BES: v_2 of identified *anti*particles vs energy

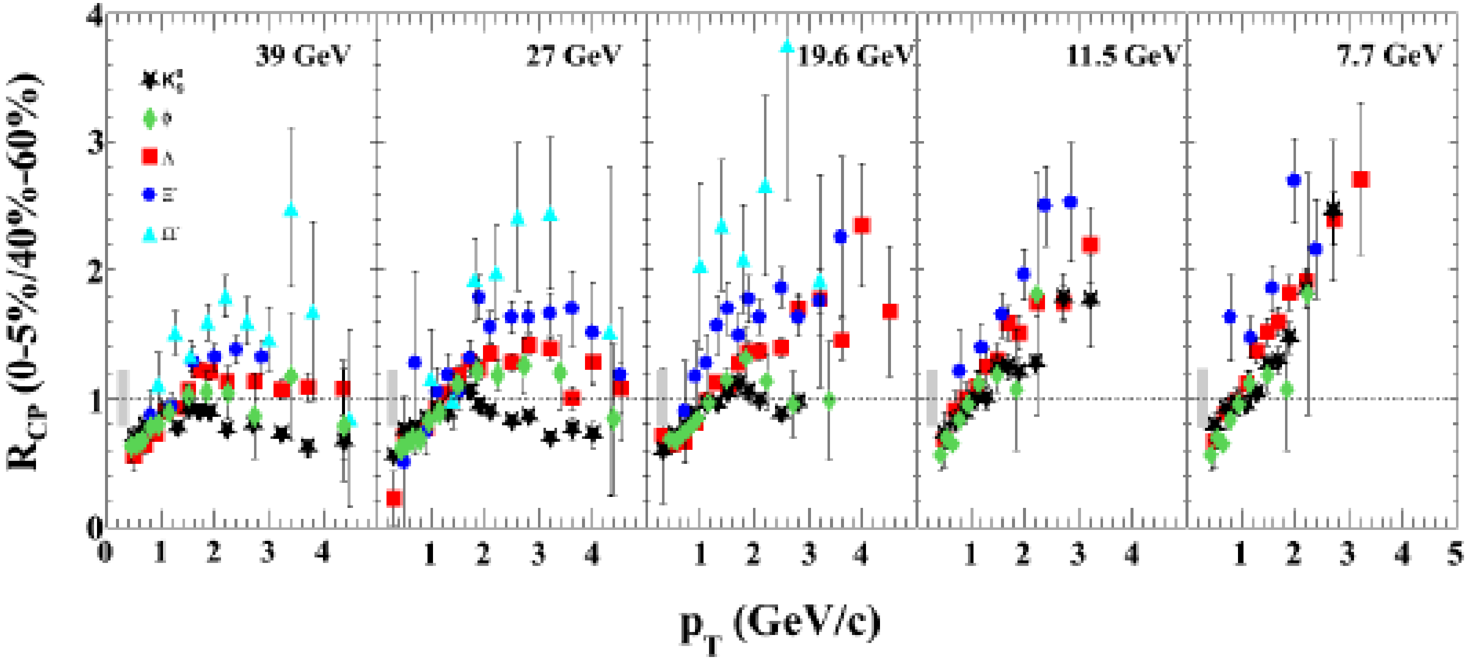
arXiv : 1301.2348 (STAR)



Baryon vs. meson splitting for ***anti***particles disappears at energies ≤11.5 GeV

R_{CP} of various strange hadrons

QM 2012 :



Baryon-meson splitting reduces with decrease of energy and at 7.7 is gone, indicating decreasing partonic effects at lower energies

For $K^0_{pt>2\ GeV/c}$: R_{CP}<1 for $\sqrt{s_{NN}}$> 19 GeV and >1 for $\sqrt{s_{NN}}$<11.5 GeV

Is there another way?

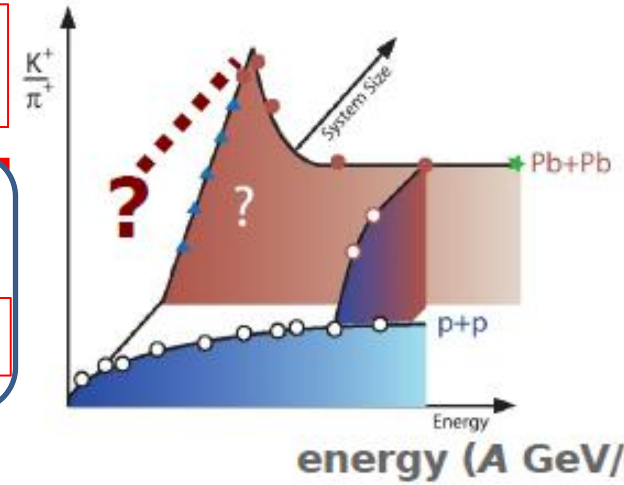
Can another facility do this faster?

Or better?

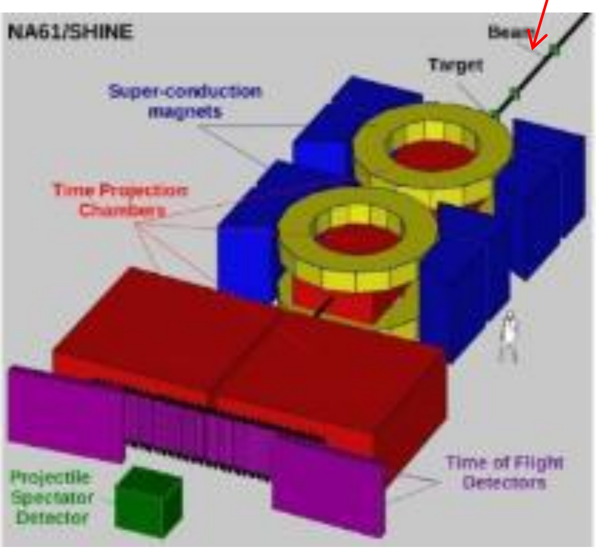
Super Proton Synchrotron (SPS)

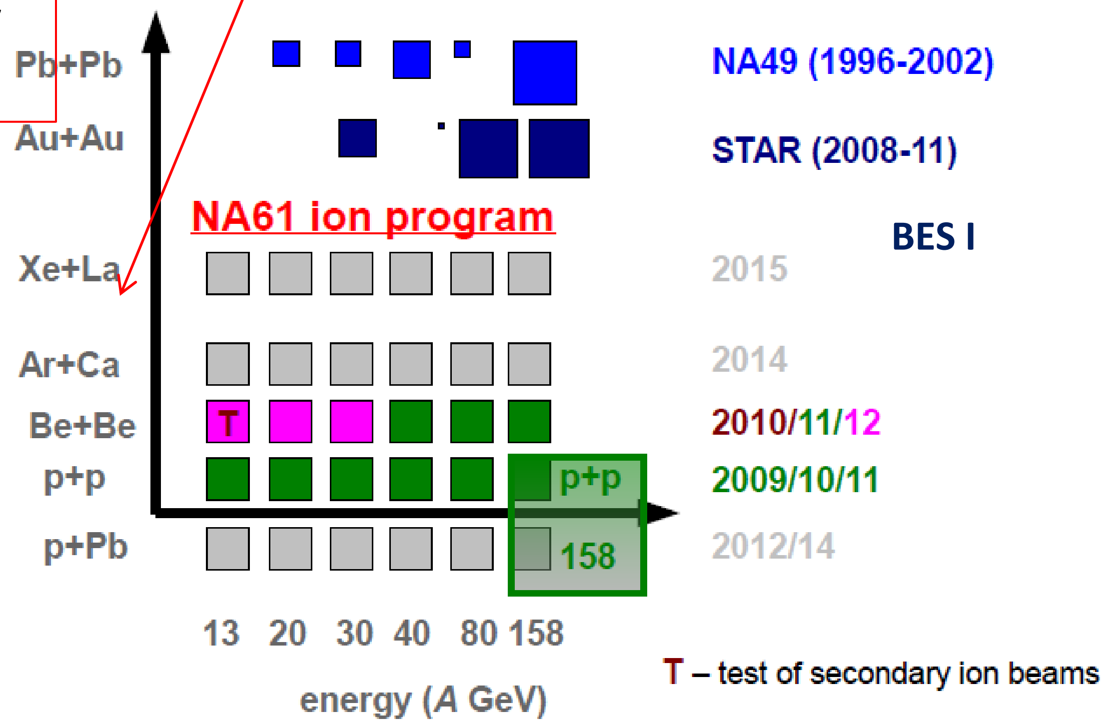
+ Running now, that's good
+ Energy range is good
- But fixed-target
- And light ions

Not Ideal



•**Time Line:** 2009-2015
•**Energy Range:** $\sqrt{s_{NN}}$ = **4.9 to 17.3** GeV
μ_B = 0.560 to 0.230 GeV

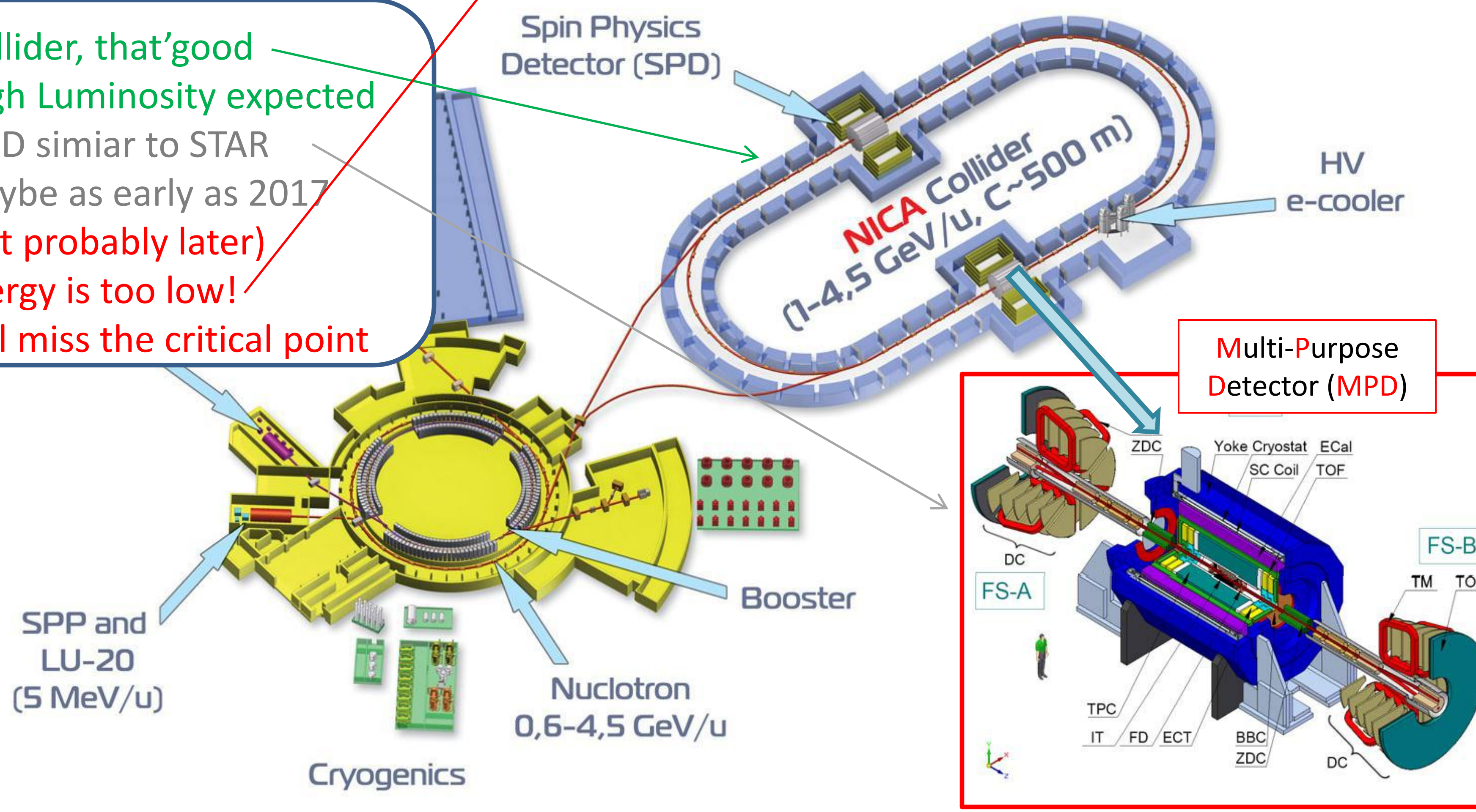




Nuclotron based Ion Collider fAcility (NICA)

- **Time Line:** Not yet funded. Plan is to submit documents by end of 2012.
  Operations could not begin before 2017 (probably much later)
- **Energy Range:** $\sqrt{s_{NN}}$ from **3.9 - 11 GeV** for Au+Au; μ_B from 0.630 - 0.325 GeV.

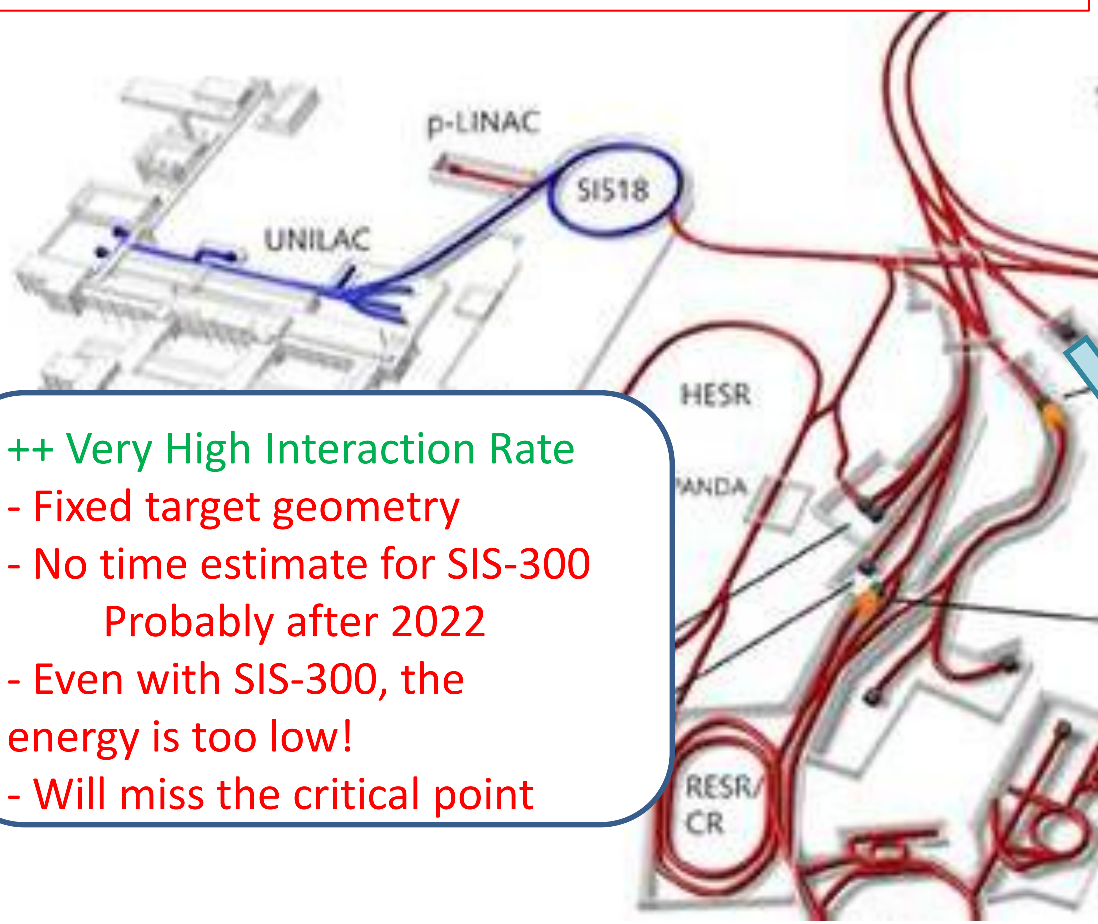
+ Collider, that'good
+ High Luminosity expected
• MPD simiar to STAR
• Maybe as early as 2017
- (But probably later)
- Energy is too low!
- Will miss the critical point



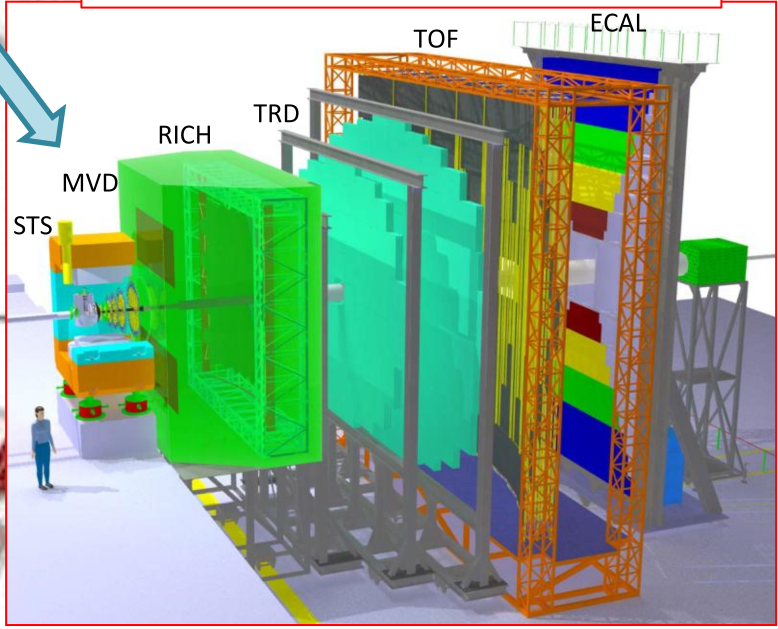
Facility for Antiproton and Ion Research (FAIR)

Time Line:
SIS-100 is funded and will be complete by 2018
SIS-300 will need additional funding (**no time estimate**)

Energy Range:
SIS-100: Au+Au @ 2.9 GeV
SIS-300: Au+Au from **2.7 to 8.2** GeV
μ_B from 0.730 to 0.410 GeV



Compressed Baryonic Matter (CBM)



- ++ Very High Interaction Rate
- - Fixed target geometry
- - No time estimate for SIS-300
  Probably after 2022
- - Even with SIS-300, the energy is too low!
- - Will miss the critical point

Comparison of Facilities

Facilty	RHIC BESII	SPS	NICA	SIS-300
Exp.:	STAR PHENIX	NA61	MPD	CBM
Start:	2017	2009	>2017?	>2022?
Au+Au Energy: $\sqrt{s_{NN}}$ (GeV)	7.7– 19.6+	4.9-17.3	2.7 - 11	2.7-8.2
Event Rate: At 8 GeV	100 HZ	100 HZ	<10 kHz	<10 MHZ
Physics:	CP&OD	CP&OD	OD&DHM	OD&DHM
		Fixed Target Lighter ion collisions		Fixed Target

CP = Critical Point
OD = Onset of Deconfinement
DHM = Dense Hadronic Matter

Conclusion:
RHIC is the best option